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DAYCENT model analysis of past and contemporary soil N_2O and net greenhouse gas flux for major crops in the USA

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Abstract

The DAYCENT ecosystem model (a daily version of CENTURY) and an emission factor (EF) methodology used by the Intergovernmental Panel on Climate Change were used to estimate direct and indirect N_2O emission for major cropping systems in the USA. The EF methodology is currently used for the USA greenhouse gas inventory but process based models, such as DAYCENT, may yield more reliable results because they account for factors such as soil type, climate, and tillage intensity that are ignored by EF. Comparison of mean annual soil N_2O flux estimated by DAYCENT and EF with measured data for different cropping systems yielded r^2 values of 0.74 and 0.67, and mean deviations of −6 and +13%, respectively. At the national scale, DAYCENT simulation of total N_2O emission was ~25% lower than estimated using EF. For both models, N_2O emission was highest in the central USA followed by the northwest, southwest, southeast, and northeast regions. The models simulated roughly equivalent direct N_2O emission from fertilized crops, but EF estimated greater direct N_2O emission than DAYCENT for N-fixing crops. DAYCENT and EF estimates of the gaseous component of indirect N_2O emission ($NO + NH_3$) differed little, but DAYCENT estimated approximately twice the indirect emission from NO_3 leaching since it included the contribution of N from N-fixing crops while EF did not. DAYCENT simulations were also performed for no tillage cropping, pre-1940 crop management, and native vegetation. DAYCENT-simulated N_2O, CO_2, and CH_4 fluxes were converted to CO_2–C equivalents and combined with fuel use estimates to estimate net global warming potential (GWP_{net}). GWP_{net} for recent non-rice (*Oryza sativa* L.) major cropping was 0.43 Mg C ha^{-1} yr^{-1} under conventional tillage and 0.29 Mg C ha^{-1} yr^{-1} under no tillage, for pre-industrial cropping was 0.25 Mg C ha^{-1} yr^{-1}, and for native systems was −0.15 Mg C ha^{-1} yr^{-1}. Results from DAYCENT suggest that conversion to no tillage at the national scale could mitigate ~20% of USA agricultural emission or ~1.5% of total USA emission of greenhouse gases.

Keywords: Biogeochemical modeling; Global warming potential; Methane; Nitrous oxide; Regional analysis; Soil carbon

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1. Introduction

1.1. Nitrogen gas emissions from agricultural soils

There has been concern regarding the environmental effects of nitrogen (N) gases in the atmosphere for many years (CAST, 1976; Rodhe, 1990). Nitrous oxide (N_2O) in the troposphere absorbs terrestrial thermal radiation and thus contributes to greenhouse warming of the atmosphere. On a mass basis, N_2O is about 300 times more potent than carbon dioxide (CO_2) in this respect, and it is increasing in atmospheric concentration at the rate of 0.6–0.9 ppbv per year (Albritton and Meira Filho, 2001; CMDL, 2002). Nitrous oxide is also involved in the depletion of the ozone layer in the stratosphere, which protects the biosphere from the harmful effects of solar ultraviolet radiation (Crutzen, 1981). It has been estimated that doubling the concentration of N_2O in the atmosphere would result in a 10% decrease in the ozone layer, and this would increase the ultraviolet radiation reaching the earth by 20% (Crutzen and Ehhalt, 1977). With a relatively long atmospheric lifetime for N_2O of approximately 114 years (Albritton and Meira Filho, 2001), there are justifiable reasons for concern. A second important atmospheric gas is nitric oxide (NO), which reacts with hydroxyl radicals in the atmosphere. Hydroxyl radicals are necessary for the removal of other greenhouse gases (GHG), such as methane (CH_4) (Williams et al., 1992). Atmospheric NO can also be deposited on soils, incorporated into the N cycle, and act as a secondary source for N_2O emission. A third reactive N gas is ammonia (NH_3), which affects visibility, aerosol chemistry, acid deposition, health, and climate. Ammonia also affects the capacity of soil to act as a sink for CH_4 (Steudler et al., 1989), which is also an important GHG. Ammonia, like NO, has a short lifetime in the atmosphere and provides a secondary source for the formation of N_2O, because it can be deposited on soils.

Globally, approximately 7 (6–13) Tg of N_2O–N is emitted to the atmosphere each year as a result of human activities (Kroeze et al., 1999). The only known process for its removal from the atmosphere is reaction with excited singlet oxygen atoms (formed by photolysis of ozone) in the stratosphere. The concentration of N_2O in the atmosphere is increasing at the rate of 0.8 ppbv yr^{-1}, which translates to an atmospheric stock increase of ~5 (4–6) Tg N yr^{-1}. Assuming that the stratospheric destruction of N_2O is 12.3 (10–15) Tg N yr^{-1} then the total emission of N_2O from the biosphere is calculated as 17.2 (14–21) Tg N yr^{-1} (Albritton and Meira Filho, 2001). These estimates suggest that the bulk of emission (~10 Tg N yr^{-1}) comes from natural sources, with oceans responsible for a third, and soils two-thirds of these emissions. Although significant uncertainty remains about the quantity of N_2O emitted from specific sources, agriculture, through soil emission, biomass burning and animal production, is responsible for an estimated 80% of anthropogenic emission (Kroeze et al., 1999).

Currently the inventory of GHG emissions and sinks in the USA includes an assessment of N_2O emission from agricultural soil based on the Good Practice 2000 amendment of the IPCC (1997) (USEPA, 2002). Calculation of N_2O emission directly from crop production systems is based on an emission factor of 1.25 ± 1% of total N applied (IPCC, 1997). However, the IPCC (1997) guidelines for estimating N_2O emission from agricultural soils have a number of limitations. The guidelines consider all agricultural systems to be the same throughout the world and do not take into account different crops, soils, climate and management, all of which are known to affect nitrification–denitrification and N_2O production and emission (Mosier et al., 1998). This methodology assumes that cropped systems are in steady-state so that the entire N cycle occurs during a calendar year, i.e., N is not stored in the plant/soil system for >1 year. However, N can be stored and cycled within the plant/soil system for many years before it is harvested, lost to the atmosphere, or leached as nitrate (NO_3) into groundwater (Follett, 2001a). This lag time between N input and ultimate production of N_2O (Bakken and Bleken, 1998; Mosier and Kroeze, 2000) and an interaction between weather patterns from year to year (Dobbie et al., 1999), are likely confounding factors that are not accounted for in the IPCC (1997) methodology.

A recent compilation of measured N_2O emission suggests that a more appropriate median N_2O emission factor would be 0.9% of N applied (Bouwman et al., 2002a; Laegried and Aastveit, 2002) instead of 1.25% as used by IPCC (1997). Whatever emission factor is used, however, it is clear that N_2O emission varies temporally and spatially and that any emission factor used would have uncertainty of >50% (Mosier et al., 1999; Lim et al., 1999). Yearly variations in N_2O emission are often greater than management-induced variations (Clayton et al., 1997; Kaiser et al., 1998). Along with emphasizing the need for appropriate field research to evaluate the impacts of management on agricultural N_2O emission, Laegried and Aastveit (2002) noted several factors other than N fertilization that would impact N_2O emissions:

- mixture of organic and inorganic fertilizers could emit more N_2O than inorganic fertilizers alone;
- crop type;
- soil organic carbon enhances N_2O emission;
- poorly drained soils could emit more N_2O than well-drained soils.

Uncertainty in indirect N_2O emission from crop and livestock production is even greater than for direct emission (Mosier et al., 1998; Nevison, 2000; Groffman et al., 2000, 2002). Indirect N_2O emission is from: (1) NO_3 leached into groundwater and subsequently, denitrified to N_2O and (2) NH_3 and NO_x emission deposited onto aquatic and soil surfaces and converted to N_2O. Groffman et al. (2002) suggested that an indirect N_2O emission requires knowledge not only of the amount of N leaching or running off from fields, but also the variation of N_2O:N_2 and N_2O:NO_x ratios resulting from different soil, sediment and aquatic conditions. They noted that while analyses of N flows in agricultural watersheds are relatively common for water quality purposes, N_2O emission is rarely measured. Compared to the IPCC (1997) methodology, process-based models should have greater potential to reduce uncertainties for both direct and indirect N_2O emissions, because they could account for how climate, soil type, and N inputs affect both total N losses and the proportion of losses that are in the form of N_2O, NO_x, NH_3, and N_2 gasses, and NO_3 leaching.

1.2. Net global warming potential (GWP_{net})

Although N_2O is a major contributor to GWP in crop production systems, the entire suite of GHGs (CO_2, N_2O, and CH_4) needs to be considered. When all GHGs are accounted, agriculture is responsible for only a small portion (~8%) of total GHG emission in the USA (USEPA, 2002). However, agriculture has large potential to mitigate the increasing radiative forcing of the atmosphere. Typical crop production practices in the USA generate N_2O and reduce the potential of soil to absorb CH_4 (Robertson et al., 2000). Improved management could store C in soil (Follett, 2001b) and decrease N_2O emission (Kroeze et al., 1999). Mitigation by agriculture could also come from reducing fossil-fuel derived energy inputs, decreasing CH_4 emission and increasing soil CH_4 oxidation. Lal (2004) estimated that C sequestration in agricultural and degraded soils could offset 5–15% of global CO_2 emission. But management strategies meant to sequester C should also be evaluated for their effects on N_2O and CH_4 fluxes, and vice versa. For example, drainage of rice paddies decreases CH_4 emission (Wassmann et al., 2000), but increases N_2O emission (Bronson et al., 1997). The overall balance between the net exchanges of these gases constitutes the GWP_{net} of a crop or livestock production system. Global warming potential is calculated in units of CO_2 equivalents by using molecular stoichiometry and assuming that N_2O and CH_4 have 296 and 23 times, respectively, the atmospheric radiative forcing of CO_2 on a per mass basis (Albritton and Meira Filho, 2001). Methane is produced mainly through enteric fermentation in livestock and through the handling of animal manure in anaerobic lagoon systems (Prather et al., 1995). Saturated agricultural soils are emitters of CH_4 and drained soils are small sinks for atmospheric CH_4 (Prather et al., 1995). Nitrous oxide, a soil-derived GHG second in importance to CO_2, is produced through microbial processes of nitrification and denitrification (Conrad, 1996). Nitrogen fertilizer input to facilitate crop production accentuates N_2O production (Bouwman et al., 2002b).

The main components of GWP from cropping systems are soil N_2O emission, plant/soil system CO_2 flux, soil CH_4 flux, and CO_2 emission from agricultural inputs and farm equipment operation. Emission of CO_2 from inputs and equipment operation include: (1) fuel used by farm machinery to plant, till, harvest, irrigate, and apply amendments and (2) fuel used to produce and transport lime, fertilizer, pesticides and herbicides (West and Marland, 2002). For agriculture in the USA, N_2O and CH_4 emissions contribute the greatest portion to the total GWP_{net}, which is estimated at 120 Tg C yr^{-1} (Fig. 1).

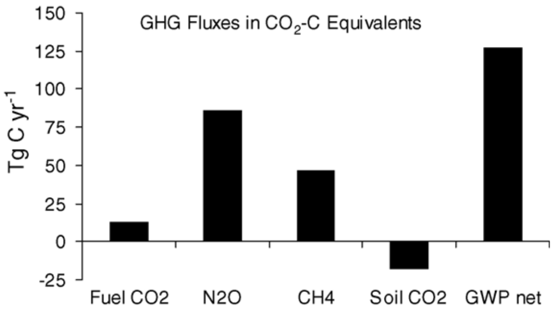

Fig. 1. Anthropogenic greenhouse gas fluxes ((+) emission and (−) sink) in the USA for 2000 (USEPA, 2002). Fuel CO_2 includes manufacturing and transport of farm amendments and operating farm machinery. GWP_{net} is net global warming potential.

Robertson et al. (2000) provided an example of the impact of tillage on GWP in a rainfed crop production system in Michigan (Fig. 2). Fuel use contributed most to GWP_{net} followed by N_2O. With 10 years of no-till cropping, C was sequestered in soil at 0.30 Mg C ha^{-1} yr^{-1}. Methane uptake by soil did not differ between tillage systems and contributed little to GWP_{net}. As a result of the no-till system storing C and conventional till being roughly soil C neutral, GWP_{net} was 0.31 Mg C ha^{-1} yr^{-1} in the conventional till system and 0.04 Mg C ha^{-1} yr^{-1} in the no-till system. However, as soils become saturated in organic matter the benefit of no-till in terms of C storage is likely to decrease.

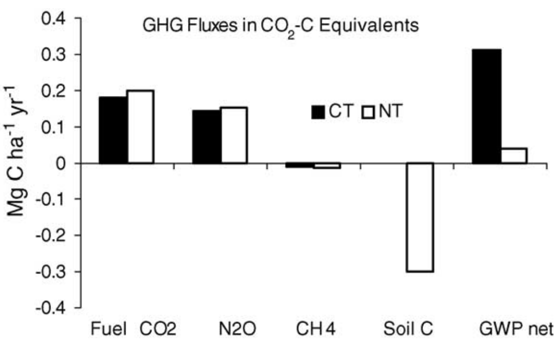

Fig. 2. Effect of tillage on net global warming potential (GWP_{net}) in a long-term corn-soybean study in Michigan (Robertson et al., 2000). Fuel CO_2 includes manufacturing and transport of farm amendments and operating farm machinery. CT = conventional tillage, NT = no tillage. Differences between CT and NT are significant only for soil CO_2 and GWP net.

Regional and national assessments of N_2O for the USA by process-based models are limited (Li et al., 1996; Mummey et al., 1998) and no process-based models have been used for national GWP calculations. Marland et al. (2003) calculated the impact of converting croplands from conventional to no tillage on GWP_{net}, but N_2O emission was calculated with a high emission factor of $2 \pm 1\%$ of applied N. The daily version of the ecosystem, process-based CENTURY model (DAYCENT) was developed to permit more realistic analyses of trace gas (CO_2, CH_4 oxidation, N_2O, and NO) exchange between the soil and the atmosphere on a daily basis. Our objective was to use DAYCENT to estimate N_2O emission and GWP_{net} for regional and national scales under these situations: (1) recent modern agriculture; (2) pre-1940 management; (3) native vegetation. Net GWP includes crop/soil system CO_2 flux, N_2O emission, CH_4 uptake, and fuel CO_2 costs of farm machinery operation and production and transport of farm inputs. Direct N_2O emission as well as indirect emission from NO_3 leaching and NO emission, were calculated. The major crop production systems within each region were used and changes in crop production management with time were included. Changes in fertilizer input, crop rotation, crop cultivars, and tillage intensity were the most notable. Estimates of N_2O emission were compared between DAYCENT and IPCC (1997) emission factor (EF) methodology. Using DAYCENT, we estimated national N_2O emission and GWP_{net} for major cropping systems in the USA under conventional and no tillage.

2. Model descriptions and testing

DAYCENT is the daily time step version of the CENTURY (Parton et al., 1994) biogeochemical model. DAYCENT (Del Grosso et al., 2001; Parton et al., 1998) simulates fluxes of C and N between the atmosphere, vegetation, and soil. Plant growth is controlled by nutrient availability, water, and temperature. Nutrient supply is a function of soil organic matter (SOM) decomposition and external nutrient additions. Daily maximum/minimum temperature and precipitation, timing and description of management events (e.g. fertilization, tillage, harvest), and soil texture data are needed as model inputs. Key submodels include plant production, SOM decomposition, soil water and temperature by layer, nitrification and denitrification, and CH_4 oxidation. Recent improvements in DAYCENT include the effect of solar radiation on plant growth rates, increased precision in the scheduling of management events, and the option of simulating seed germination as a function of soil temperature and harvest or senescence as a function of growing degree days accumulated since germination. Comparison of model results and plot data have shown that DAYCENT reliably simulates crop yield, SOM levels, and trace gas flux for various native and managed systems (Del Grosso et al., 2002).

IPCC (1997) guidelines assume that 1.25% of unvolatilized N inputs are lost from soil as direct N_2O emission, 10% of N applied is released as NO + NH_3, and 30% of applied N is leached or runs off into groundwater or surface waters. N inputs for calculating direct N_2O emission include fertilizer and organic amendments, N fixation, and plant residue that were not removed during harvesting. N input from N-fixing crops [soybean (*Glycine max* (L.) Merr.), alfalfa (*Medicago sativa* L.)] is 3% of total aboveground dry matter production. Residue N input for wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), and soybean is 0.62, 0.58 and 2.3%, respectively, of total aboveground-unharvested dry matter. The US Environmental Protection Agency has not included the IPCC background N_2O emission in calculations for the USA, because the goal of the inventory has been to estimate anthropogenic emission. We included the IPCC background N_2O emission of 1 kg N_2O–N ha^{-1} yr^{-1} for EF estimates, because both measurements and DAYCENT simulations represent total N_2O emission. Indirect N_2O emission was defined as the sum of 1% of NO_x + NH_3 gases emitted and 2.5% of NO_3 leached to surface or ground waters.

An important difference between EF methodology and DAYCENT relates to assumptions regarding N cycling. EF assumes that N added to a system in one year completely cycles during that year, e.g. N added as fertilizer or through fixation contributes to N_2O emission for that year, but cannot be stored in soil or biomass and be recycled and contribute to N_2O emission in subsequent years. In contrast, DAYCENT includes legacy effects such that N added to the system in 1 year may be taken up by vegetation and returned to the soil in organic form during that year, then re-mineralized and emitted as N_2O in following years. In addition to previous year's fertilizer additions, other long-term management practices that affect current SOM level (e.g., intensive cultivation, summer fallow) also affect current N_2O emission, because in models such as DAYCENT, N from internal cycling (mineralization of SOM) contributes to N_2O emission. Thus, while EF estimates are influenced only by the current year's N inputs, DAYCENT emissions are also influenced by management in previous years. In the broader context, empirical models such as EF methodology, and process-based models such as DAYCENT, have distinct advantages and disadvantages. Empirical models use easy to acquire input data (e.g., total N inputs to cropped land) and are easy to apply, requiring only spreadsheet calculations. Process-based models require more detailed inputs (e.g.,

Table 1
Characteristics of data used for model testing

Site	Crops	Components evaluated	Time	Source
Iowa A	Corn, soybean	Grain yield, NO_3 leaching	1996–1999	Jaynes et al. (2001)
Iowa B	Fertilized fallow/soybean	N_2O	1979	Bremner et al. (1981)
Wisconsin A	Corn, potato	Grain yield, NO_3 leaching	1993–1994	Stites and Kraft (2001)
Wisconsin B	Corn	Grain yield, NO_3 leaching	1992–1993	Andraski et al. (2000)
Michigan A	Alfalfa	Grain yield, N_2O	1991–1999	Robertson et al. (2000)
Michigan B	Corn, soybean, wheat	Hay yield, N_2O	1991–1999	Robertson et al. (2000)
Nebraska	Wheat/fallow	Grain yield, N_2O	1993–1995	Kessavalou et al. (1998)
Colorado A	Wheat/fallow	N_2O	1993–1995	Mosier et al. (1997)
Colorado B	Irrigated corn	N_2O	1992	Mosier et al. (1986)
Colorado C	Irrigated barley	N_2O	1993	Mosier et al. (1986)
Tennessee	No till corn	N_2O	1993	Thornton and Valente (1996)
Ontario	Corn	Grain yield, N_2O	1998	Grant and Pattey (2003)

crop specific N input rates) and large amounts of computing time and programming expertise. Process-based models can potentially yield more reliable results, because they account for more of the key controls, but results are limited by the quality of input data and resources available for model evaluation and application.

A variety of field data were used for model validation of N_2O emission, NO_3 leaching, and crop yield (Table 1). Land management and soil data required for model inputs were from references in Table 1, while daily weather data needed to drive DAYCENT were obtained from the authors or from weather stations close to the test sites. Input parameters controlling crop growth rates, NO_3 solubility, etc. were consistent for all the sites used for model testing. The only model inputs changed for different simulations were climate, soil physical properties, crop rotation, and land management schedules. Results in Fig. 3 are means for all years and treatments reported in Table 1. Measured and simulated output were evaluated using coefficient of determination (r^2), root mean square error (rmse), bias and deviation. Bias was defined as the tendency for model output to overestimate low values and under-estimate high values. Bias was quantified by linear regression of simulated versus measured values. Bias was small when slope was near 1 and intercept was near 0. Deviation was calculated as the difference between simulated and measured values divided by the measured value.

Both models captured major differences, but EF over-estimated mean N_2O for sites with low emission and both models under-estimated N_2O for two sites with high emission (Fig. 3a). DAYCENT was within 33% of measured values for all data sets except Colorado C. Across sites, DAYCENT under-estimated N_2O emission by 6% and EF methodology over-

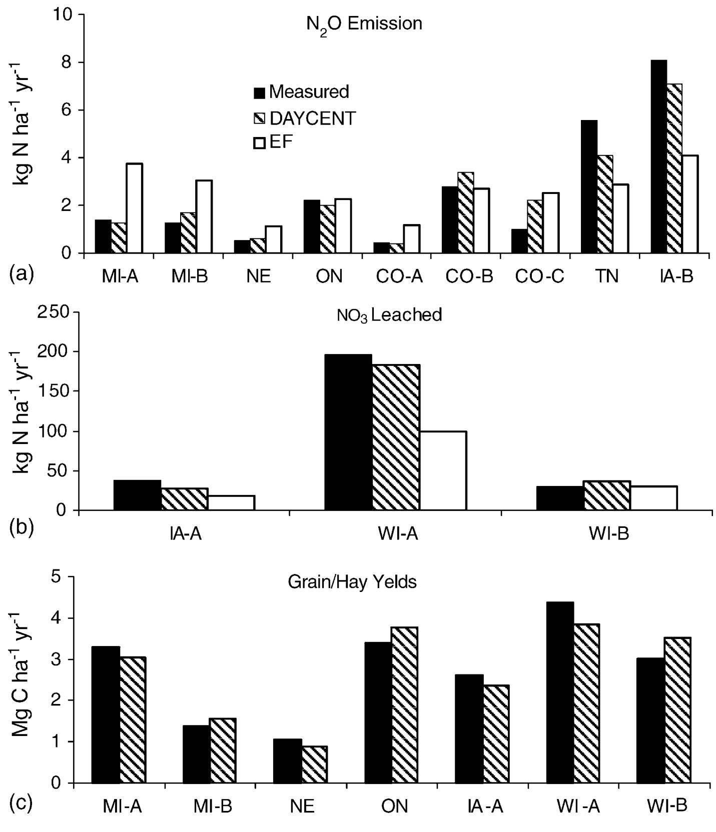

Fig. 3. Comparison of measured, DAYCENT-simulated, and IPCC emission factor (EF)-estimated (a) direct soil N_2O emission, (b) NO_3 leaching, and (c) crop yield for sites described in Table 1.

estimated emission by 13%. Fig. 4a shows simulated versus measured N_2O emission for the different soils and treatments ($n = 21$) represented in Fig. 3a. Regressions indicated that EF was more biased than DAYCENT.

Nitrate leaching was estimated with maximum deviation <30% using DAYCENT, but under-estimated by ~50% at two of the three sites using EF (Fig. 3b). Regression of simulated versus measured NO_3 leaching indicated that DAYCENT had little bias, but EF under-estimated large values (Fig. 4b). The EF underestimate of NO_3 leaching may have been in part due to the fact that only N from fertilizer and manure were considered available for leaching, while DAYCENT considered the N derived from crop N-fixation as well. Crop yield was relatively accurate when predicted by DAYCENT (Fig. 3c, $r^2 = 0.90$, maximum deviation = 22%, rmse = 13%).

3. Regional simulations

The contiguous USA was divided into 63 minor agricultural regions as used by the Agricultural Sector Model (McCarl et al., 1993). Each state in the contiguous USA coincided with a minor region, except that some states were divided into two or more minor regions. The 63 minor regions were combined into five major agricultural regions. Table 2 defines the regions and describes major crops and areas in each. Climate, soil, and land management data required to run DAYCENT at the minor regional scale were

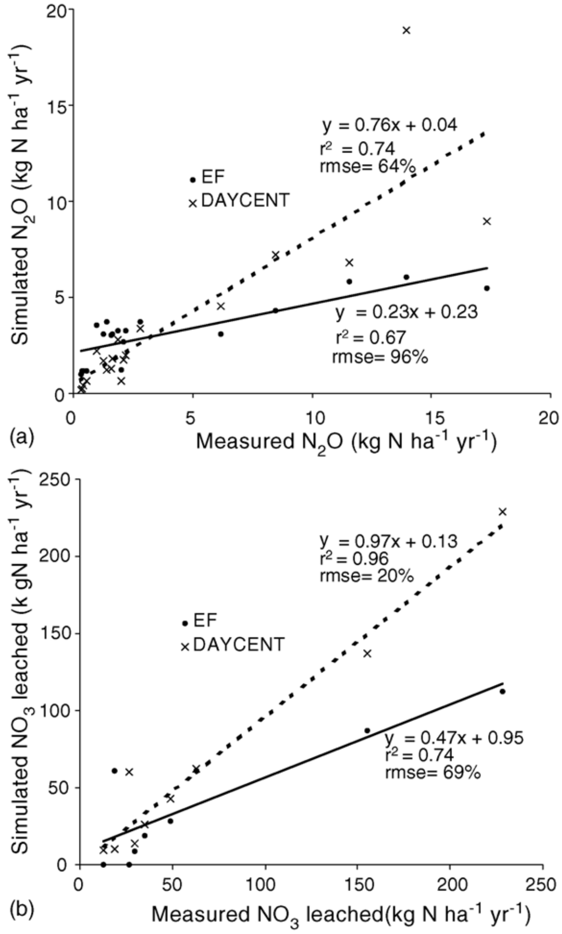

Fig. 4. Relationship of measured, DAYCENT-simulated, and IPCC emission factor (EF)-estimated (a) N_2O emission and (b) NO_3 leaching for different conditions for the sites listed in Table 1.

Table 2
Regional characteristics of DAYCENT simulations

Major regions	Minor regions	Crops simulated	Crop area simulated (Mha)
Northeast	WI, MI, NY, VT, NH, ME, RI, CT, MA, NJ, DE	Hay, corn, soybean	7.2
Central	PA, WV, KY, TN, OH (3 zones), IN (2 zones), IL (2 zones), IA (4 zones) MO, MN	Corn, soybean, hay	47
Southeast	VA, MD, NC, SC, GA, FL, AL, MS, LA, AR	Corn, soybean, hay, rice, cotton	11
Southwest	OK, TX (8 zones), NM, AZ, UT, NV, CA (2 zones)	Corn, soybean, hay, rice, cotton, wheat, sorghum	18.6
Northwest	KS, NE, SD, ND, CO, WY, MT, ID, OR, WA	Corn, soybean, hay, wheat, barley	39.4

acquired from different sources. We used the Erosion-Productivity Impact Calculator (EPIC; Sharpley and Williams, 1990) model to obtain soil texture classifications and 100 years of daily climate for each minor region. Climate from EPIC was computer generated, but constrained by actual climate. The data set did not reflect any long-term changes in climate. Soil physical properties needed for model input were calculated from texture class and a hydraulic property calculator (http://www.bsyse.wsu.edu/saxton/soilwater/; Saxton et al., 1986). Land management data for each minor region were compiled using modern and historical records of crop yield, area, and inputs. Native vegetation for each minor region was assumed to be the potential vegetation from VEMAP (1995). Crop area and yield data were downloaded from the web site of the National Agricultural Statistics Service of the United States Department of Agriculture (http://www.nass.usda.gov:81/ipedb/).

Four sets of simulations were performed for each minor region: (1) native vegetation (year 1 to plow out); (2) historical agricultural practices (plow out to 1970); (3) modern agriculture (1971–2000) with conventional tillage; (4) modern agriculture (1971–2000) with no tillage. The 100-year cycle of computer-generated modern climate was repeated to drive native and historical simulations. Climate did not reflect long-term climate change, but did contain inter-annual variability. Plow out was assumed to occur between 1601 and 1850, depending on minor region. Simulation of at least 1600 years of native vegetation was needed to initialize SOM pools and to provide baseline GHG flux levels to compare with agriculture. Simulation of plow out and historical cropping were needed to assess GHG fluxes for pre-1940 agriculture and to establish modern SOM levels. Simulations for modern agriculture (1971–2000) included a sufficient number of crop rotations so that $\geq$80% of the reported crop area in most minor regions was represented. For example in Vermont, it was necessary to simulate hay and corn, while in Louisiana, corn, soybean, and cotton had to be included to cover $\geq$80% of the cropped area. In some states (e.g., Florida), crops simulated were <80% of total cropped area. For multi-year rotations (e.g. corn/soybean, wheat/corn/fallow), different simulations were performed where the initial crop was varied but the sequence was not altered to ensure that each crop was represented each year. In cases where the same crop was grown in the same year in two or more distinct rotations for a minor region, average values for each output were calculated. Simulations assumed conventional tillage until 1970, gradual improvement of cultivars, and gradual increases in fertilizer application. Post 1970 organic N amendments were not included, because EPIC, on which DAYCENT runs were based, did not include organic amendments. The model was not tuned for different minor regions, i.e. the same parameters used for the model validation described in the previous section were used for the regional simulations. We did not include cropping of histosols, which could be a strong N_2O source, and simulated only corn, soybean, wheat, alfalfa and cotton cropping systems.

Ten years of model output were compiled for each minor region for native condition (1591–1600), pre-940 management (1921–1930), and modern agriculture under conventional- and no-tillage management (1991–2000). Annual mean and standard deviation for each output variable were calculated. Climate data used to run the model did not reflect real-time changes in climate, so differences in means for the four scenarios were due entirely to changes in vegetation and land management. Standard deviations were driven by inter-annual variability in climate data. Model outputs were crop yield, net system CO_2 flux, direct N_2O emission from soil, NO_3 leaching, NH_3 volatilization, NO emission, and CH_4 oxidation. Net system CO_2 flux integrated C fixed by photosynthesis in vegetation, litter, and soil and C lost through respiration from litter and SOM. Results from simulations of the 63 minor regions were summed to obtain major regional and national totals. Using EF methodology, N inputs from fertilizer, crop residue, and N fixation were identical to those used to run DAYCENT. The EF background direct N_2O flux of 1 kg N_2O–N ha^{-1} yr^{-1} was also included to be consistent with site-level comparisons and because DAYCENT simulated total N_2O flux. For both DAYCENT and EF, indirect N_2O emission was calculated by assuming that 2.5% of NO_3 leached was emitted as N_2O from aquatic denitrification and that 1% of NO_x and NH_3 emissions was deposited and converted to N_2O in soils. Raw DAYCENT output on a per area basis and cumulative regional area for different crops were multiplied to estimate total annual emissions for the major regions and crops.

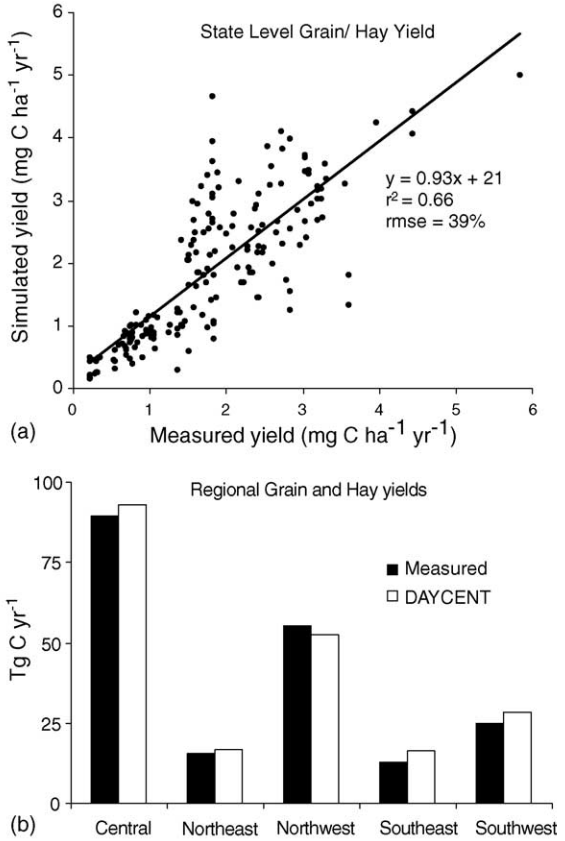

Fig. 5. Comparisons of measured and DAYCENT-simulated (a) state and (b) regional level crop yields in the USA.

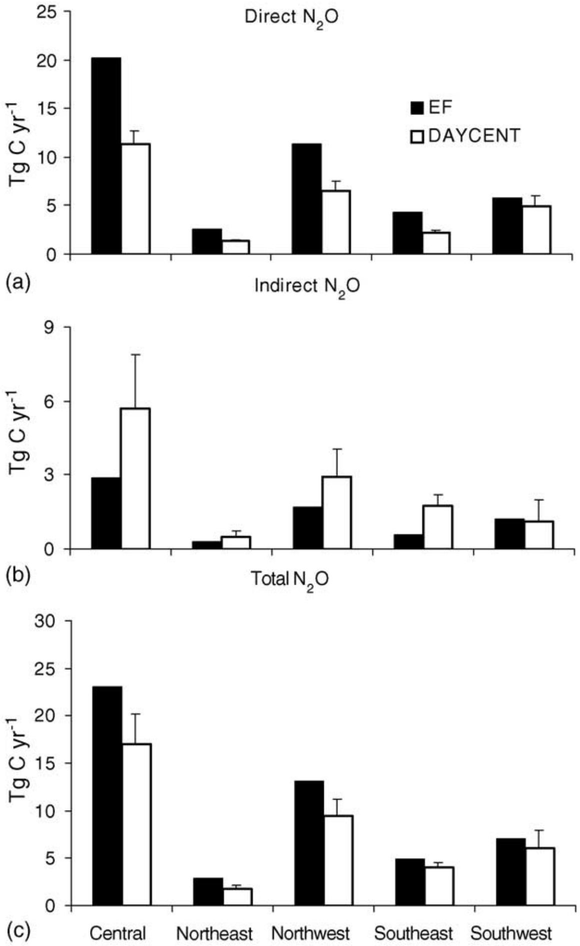

Fig. 6. Comparison of IPCC emission factor (EF)- and DAYCENT-simulated (a) direct, (b) indirect, and (c) total N_2O emissions for major agricultural regions in the USA. Results are for major crops (corn, soybean wheat, alfalfa, cotton) based on 10-year mean and standard deviation in units of CO_2–C equivalents.

4. Regional N_2O emission and GWP_{net}

DAYCENT satisfactorily ($r^2 = 0.66$, rmse = 39%) simulated measured state-average crop yields (Fig. 5a). Total yield for each major region was simulated very well (regional $r^2 = 0.99$, rmse = 7%) by the model (Fig. 5b). Within major regions, DAYCENT generally simulated lower direct and higher indirect N_2O emissions than EF (Fig. 6). Both methods had the same relative ranking of N_2O emission from the five major regions, i.e., direct and total N_2O emissions were highest in central, intermediate in northwest, southwest, and southeast, and lowest in northeast. This ranking reflected the cumulative agricultural area of each region (Table 2). Standard deviations were relatively small for direct and total N_2O emissions, but large for indirect N_2O emission. Large variation in indirect N_2O emission was probably a result of NO_3 leaching being a significant component that has a non-linear response to precipitation amount and distribution. Large precipitation events over a short time period would be necessary for significant NO_3 leaching to occur.

Simulations sorted by crop-highlighted differences between DAYCENT and EF methodology (Fig. 7). Both methods estimated similar direct N_2O emission for fertilized crops (corn, cotton, wheat), but DAYCENT simulated lower direct N_2O emission than EF for N-fixing crops (alfalfa, soybean) (Fig. 7a). EF methodology assumes that $1\ \mathrm{kg}\ N_2O\text{–}N\ \mathrm{ha}^{-1}\ \mathrm{yr}^{-1}$

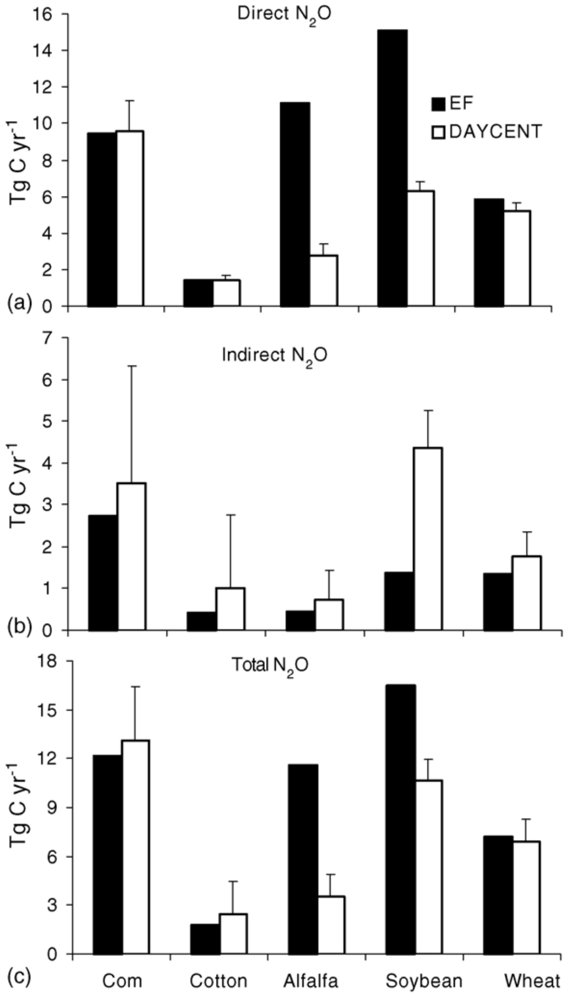

Fig. 7. Comparison of IPCC emission factor (EF)- and DAYCENT-simulated (a) direct, (b) indirect, and (c) total N_2O emissions for major crops in the USA. Results are 10-year mean and standard deviation in units of CO_2–C equivalents.

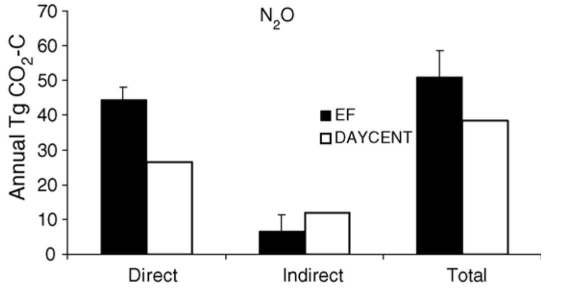

Fig. 8. Comparison of IPCC emission factor (EF)- and DAYCENT-simulated direct, indirect, and total N_2O emissions across cropping systems in the USA. Results are 10-year mean and standard deviation in units of CO_2–C equivalents.

would be emitted in unfertilized soils, which may be too high in some instances. For example, in unfertilized irrigated corn in Colorado, N_2O emission was 0.32 and 0.25 kg N ha^{-1} yr^{-1} under conventional and no tillage, respectively (A.R. Mosier, unpublished data). In contrast, DAYCENT simply estimates total N_2O. The EF methodology estimates N_2O emissions from legume crops based on aboveground biomass production, while DAYCENT estimates N_2O emission based on belowground plant N inputs, N losses, and N transformations. DAYCENT simulated higher indirect N_2O emission than EF for all of the crops, especially soybean and cotton (Fig. 7b). DAYCENT considers the N fixed by alfalfa and soybean to be susceptible to leaching, while this N component is not considered in EF. Differences in N_2O emission among crops were due to areas planted, crop-specific N fertilizer rates, and crop-specific N fixation rates. At the national scale, direct N_2O emission was 41% lower with

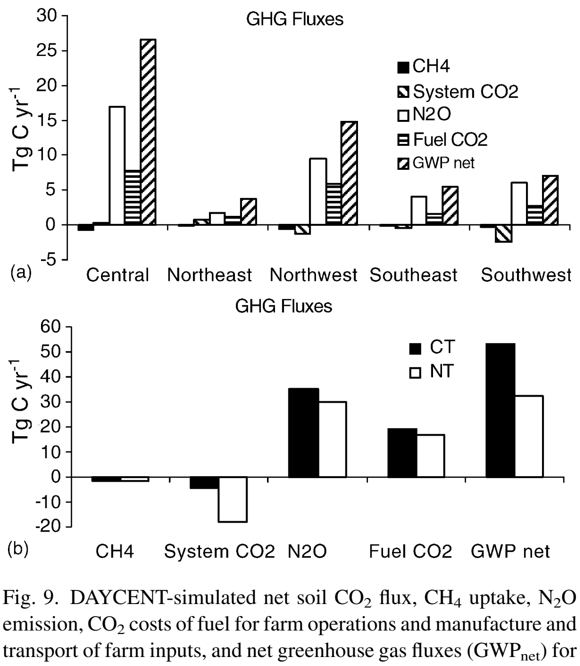

Fig. 9. DAYCENT-simulated net soil CO_2 flux, CH_4 uptake, N_2O emission, CO_2 costs of fuel for farm operations and manufacture and transport of farm inputs, and net greenhouse gas fluxes (GWP_{net}) for (a) major agricultural regions and (b) total cropland in the USA under conventional tillage (CT) and no tillage (NT). GWP_{net} is the sum of the CO_2–C equivalents of the 4 components. Results are for major crops (corn, soybean wheat, alfalfa, cotton) based on 10-year means in units of CO_2-C equivalents.

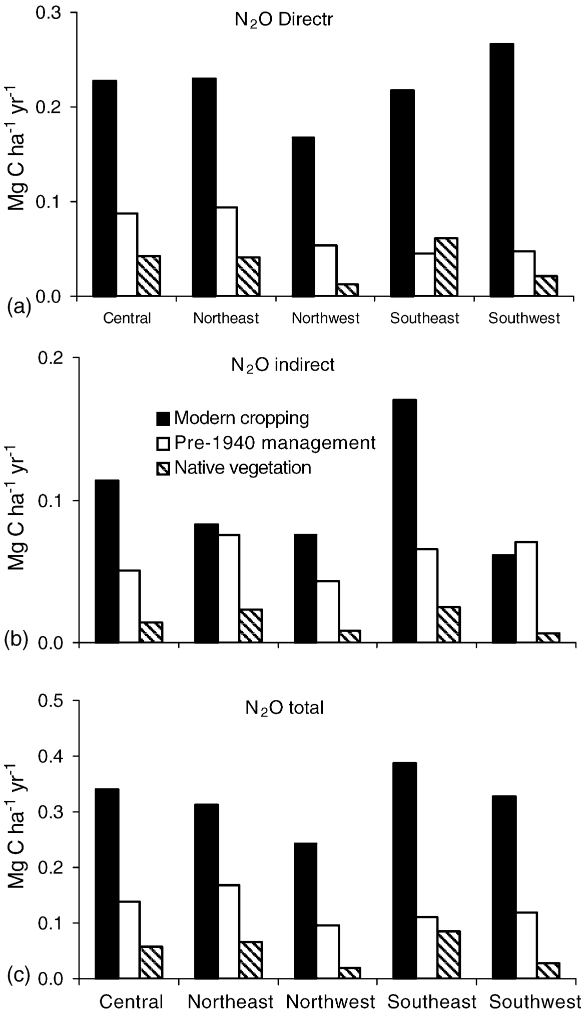

Fig. 10. DAYCENT-simulated (a) direct, (b) indirect, and (c) total N_2O emissions for modern cropping, pre-1940 management, and native vegetation in the USA. Results are based on10-year means in units of CO_2–C equivalents.

DAYCENT than EF and indirect N_2O emission was ~80% higher than EF (Fig. 8).

Net GWP varied among major regions due primarily to areas of cropping (Fig. 9a). N_2O emission was the major contributor to GWP_{net} in all major regions followed by fuel CO_2. Estimates of fuel CO_2 costs for corn, soybean, cotton, and wheat were derived from West and Marland (2002) and alfalfa fuel costs were assumed to be identical to soybean. Net system CO_2 flux was a sink in the southwest and a source in the northeast. Agriculture in the southwest was historically dominated by low C input dryland cropping, but increases in irrigation has led to high C input cropping in recent years to shift the region to a C sink. All regions were a minor sink for CH_4. The central region, which includes the majority of corn and soybean cropping in the USA, had the highest N_2O emission and GWP_{net}.

At a national level, DAYCENT simulated net system CO_2 flux as a minor sink under conventional tillage and a strong sink under no tillage (Fig. 9b). Agricultural soils were also a minor sink for CH_4. Both N_2O emission and fuel CO_2 were primary contributors to agricultural systems in the USA acting as sources of GWP_{net}. Net GWP under no tillage was ~33% lower than under conventional tillage, due to stronger net system CO_2 sink and slightly lower N_2O emission and fuel CO_2 costs (Fig. 9b).

Comparisons of modern agriculture with historical management were presented on a per area basis, because estimates of agricultural land area before ~1950 were not considered reliable. In all regions, modern agricultural soils had higher direct N_2O emission than pre-industrial agricultural systems (Fig. 10). Modern agricultural N_2O emission was >2 times that of pre-1940 management and ~6 times that of native vegetation (Fig. 11). Modern agriculture was either a minor or strong sink for net system CO_2 depending upon tillage, while pre-industrial cropping was a strong source, and native vegetation was a sink (Fig. 11). Native soils were the largest CH_4 sink and

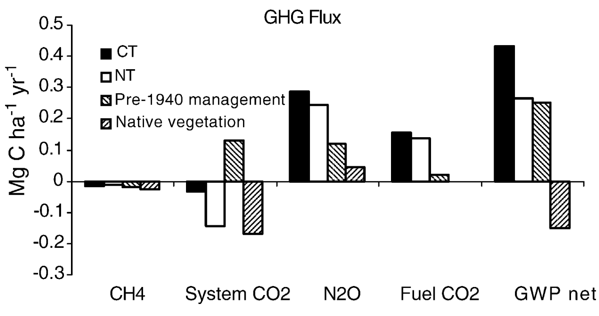

Fig. 11. DAYCENT-simulated net system CO_2 flux, CH_4 uptake, N_2O emission, CO_2 cost of fuel for farm operations and manufacture and transport of farm inputs, and net greenhouse gas fluxes (GWP_{net}) for modern cropping under conventional tillage (CT), modern cropping under no tillage (NT), pre-1940 management, and native vegetation in the USA. GWP_{net} is the sum of the CO_2-C equivalents of the four components. Values are 10-year means in units of CO_2–C equivalents.

modern agriculture the smallest. Net GWP simulated by DAYCENT suggested that modern agriculture was a source of 0.29–0.43 Mg C ha^{-1} yr^{-1}, pre-industrial agriculture was a source of 0.25 Mg C ha^{-1} yr^{-1}, and native vegetation was a sink of 0.15 Mg C ha^{-1} yr^{-1}. These estimates assumed that pre-industrial fuel costs for farm equipment operation and manufacture/transport of non-fertilizer farm amendments were negligible.

5. Discussion

Comparisons with measured data showed that while both EF and DAYCENT captured general site/treatment differences in direct soil N_2O emissions, DAYCENT had better fit (higher r^2, lower rmse, slope closer to 1, intercept closer to 0, Figs. 3a and 4a). This was not surprising since DAYCENT includes site-specific factors (climate, soil properties, previous management) that influence N_2O emission, and which were not considered using EF methodology. DAYCENT reliably simulated NO_3 leaching ($r^2 = 0.96$) while EF tended to under estimate this factor (Fig. 4b). A major reason for EF under-estimating leaching was that only N inputs from fertilizer or organic matter amendments were considered vulnerable for leaching.

DAYCENT simulated mean annual N_2O emission fairly well (Figs. 3 and 4), but daily simulations have r^2 values with observations rarely exceeding 25% (Del Grosso et al., 2002). Effects of topography, aspect, wind, humidity, microsite heterogeneity, gas diffusion, and other factors on soil water and temperature were not included in DAYCENT, but were likely important on a daily basis. There are more detailed ecosystem models that account for most of the controls on N_2O emission not included in DAYCENT (Grant and Pattey, 2003), but these models would be more difficult to parameterize and could not be easily used for regional scale simulations. We believe DAYCENT represents an appropriate compromise, because while it ignores some controls on trace gas emission, it can be run at the national level and accounts for more controls than EF methodology.

It would be inappropriate to compare these DAYCENT results with the USEPA (2002) national assessment for agricultural GHG emissions (Fig. 1), because DAYCENT results were only for major crops (corn, soybean, wheat, alfalfa, cotton). For example, DAYCENT did not simulate flooded rice paddies that would be strong emitters of CH_4, but did include upland soils that act as a sink for atmospheric CH_4. On a per cropped area or per N input basis, DAYCENT estimated lower total N_2O emission than EF (Figs. 6–8).

The biggest differences between DAYCENT and EF were in direct and indirect N_2O emissions from N-fixing crops. EF methodology assumes that only N from synthetic fertilizer and organic matter amendments was susceptible to leaching, so NO emission and NH_3 volatilization were the only sources of indirect N_2O emission from non-amended legume fields. However, Jaynes et al. (2001) showed a significant amount of NO_3 leaching during years when unfertilized soybeans were grown in rotation with corn. Di and Cameron (2002) also showed significant amount of NO_3 leaching (5–51 kg N ha^{-1}) during the unfertilized soybean phase of a rotation with corn. These data do not provide conclusive evidence that N from fixation was leached, but if measured NO_3 leaching during soybean were from fertilizer applied to corn, then IPCC methodology assuming that all N applied to a system cycles within the application year would not be correct. Higher direct N_2O emission with EF than DAYCENT was primarily due to the EF assumption that 1.25% of the total N fixed was lost as N_2O. In contrast, DAYCENT assumes that a large portion of the fixed N, typically >50%, is removed during harvest of aboveground biomass and never enters the soil mineral N pool where N cycling that results in N_2O emission occurs. Also, a portion of the soil mineral N may be leached from the soil profile to decrease NO_3 availability for denitrification. Direct measurement of N_2O emission for N-fixing crops in Michigan was more consistent with DAYCENT simulations than EF estimations (Fig. 3a). Data from alfalfa and soybean cropping in Canada (Rochette et al., 2004) also suggest that EF could over-estimate direct N_2O emission. Although atmospheric N_2 is fixed in the form of NH_3, the EF assumption that leaching is only from fertilizer and organic matter additions is almost certainly incorrect. Biologically fixed N can senesce, decompose, enter the soil N pool, be stored in the organic form for many years, be reabsorbed by plants, or be lost from the plant/soil system via leaching or N gas emission (Follett, 2001a; Paul and Clark, 1996).

Although GWP_{net} was higher for modern agriculture than pre-1940 management on a per area basis, on a per yield basis modern emission could likely be lower, because yield has more than doubled with modern cropping. In contrast to other regions, direct N_2O emission was lower for pre-1940 management than native vegetation in the southeast, because soils were depleted in SOM from cotton cultivation beginning in the 1700s. Excessive tillage and low C input to soil with pre-industrial cotton production resulted in SOM depletion, and subsequently lower N_2O emission. Indirect N_2O emission was lower for modern agriculture than pre-1940 management in the southwest, because of the extent of irrigation. Higher soil water content with irrigation increased N_2O emission and decreased NO emission. NO is an important component of indirect N_2O emission in the southwest, because rainfall would not be sufficient to leach NO_3. Pre-1940 management was a strong net system CO_2 source (Fig. 11), because soils were extensively plowed and relatively primitive cultivars supplied low C inputs to the system. CH_4 uptake was highest for native vegetation, because conversion to cropping generally inhibits the ability of soils to oxidize CH_4 (Bronson and Mosier, 1993). Modern agriculture had less CH_4 uptake than pre-1940 management, because irrigation increased and as soil water content increases, CH_4 diffusion from the atmosphere to the soil decreases (Del Grosso et al., 2000).

Differences in N_2O emission simulated by DAYCENT and estimated by EF varied among regions. This was related to the dominance of different crops in major regions and the large disagreement between the two methods for N-fixing crops (Fig. 7). Since soybean and alfalfa were a smaller proportion of total crop area in the southwest compared to most other major regions, DAYCENT and EF produced similar results. Indirect N_2O emission with DAYCENT was higher than with EF in all regions except the southwest, because leaching was expected to form a larger proportion of indirect emission with high rainfall.

Consideration of the form of N losses from a system helps explain why EF had higher total N_2O emission than DAYCENT. The sum of direct N_2O, NO, NH_3, and NO_3 leaching was approximately equal for both models. Compared to EF, DAYCENT estimated lower direct N_2O emission and higher NO_3 leaching, particularly for legumes. Only 2.5% of NO_3 leached was assumed to contribute to indirect N_2O emission, so higher NO_3 leaching and less direct N_2O emissions led to lower total N_2O emissions for DAYCENT. The other major reason for higher direct N_2O emission for EF was background N_2O emission of 1 kg N_2O–N ha^{-1}, which was likely too high for at least some crops.

6. Conclusions and future work

DAYCENT reliably simulated direct N_2O emission and NO_3 leading, but EF did not. DAYCENT also simulated state-level crop yields reasonably well ($r^2 = 66\%$, rmse = 39%). Errors may have been created by using coarse-scale climate and soil conditions. A large discrepancy occurred between EF and DAYCENT for N losses from N-fixing crops due to different assumptions. Limited observations of N_2O emission and NO_3 leaching suggest that EF may over-estimate direct N_2O emission and underestimate NO_3 leaching from legumes, although more data are needed before definitive conclusions can be drawn.

The current national N_2O assessment in the USA considers N inputs and crops grown for single years in isolation. However, there is evidence that previous year's cropping influences subsequent year's N_2O emission. For example, N_2O emission was higher from irrigated corn following soybean than from corn grown continuously, even though fertilizer input for corn was identical (A.R. Mosier, unpublished data). This evidence supports the suggestion by Bakken and Bleken (1998) that N_2O emission factors should be based on multiple years and not based on the assumption that the N that is applied to a system in one year is entirely cycled during that year. DAYCENT and other process-based models could account for the effects of previous land use on any given year's N_2O emission by allowing for N storage in biomass, litter, SOM, and mineral soil N. However, agricultural statistics in the USA typically quantify areas for different crops in isolation, not accounting for crop rotations. Availability of rotation-based crop area would provide an opportunity to increase confidence in estimated N_2O emission.

DAYCENT simulations of national GWP_{net} fluxes from major crops in the USA were limited by the use of coarse spatial-scale (state or sub-state level) computer-generated daily climate and coarse spatial-scale soil data. Further DAYCENT simulations using county-level data (including manure inputs) need to be conducted. Real-time county-level climate and county level soils data should improve model agreement with measured crop yield and increase confidence in DAYCENT-simulated GWP_{net} estimates. Future simulations should cover more cropped area, include pastures, and determine effects of precision fertilizer application on GWP_{net}. Methodologies to quantify confidence intervals similar to those presented by Ogle et al. (2003) need to be developed and applied to means simulated by DAYCENT.

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